Spectral Analysis of Mid-IR Excesses of WDs

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Abstract. In our *Spitzer* 24 μm survey of hot white dwarfs (WDs) and archival *Spitzer* study of pre-WDs, i.e., central stars of planetary nebulae (CSPNs), we found mid-IR excesses for ~15 WDs/pre-WDs. These mid-IR excesses are indicative of the presence of circumstellar dust that could be produced by sub-planetary objects. To further assess the nature of these IR-excesses, we have obtained *Spitzer* IRS, Gemini NIRI and Michelle, and KPNO 4m echelle spectra of these objects. In this paper we present the analysis of these spectroscopic observations and discuss the nature of these IR excesses.

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DUST DISK AROUND THE CENTRAL STAR OF THE HELIX NEBULA

The central star of the Helix Nebula is a hot white dwarf (WD) with an effective temperature of $\sim 110,000$ K. Its *Spitzer Space Telescope* MIPS 24 and 70 μm observations have revealed a compact source coincident with the central WD. A follow-up Infra-Red Spectrograph (IRS) observation of the central point source has confirmed that the mid-IR emission originates from a dust continuum with a temperature of $90-130$ K, and an emitting area of $4-40$ AU^2. Only an extended object, such as a dust disk, can explain these properties. The location of the dust, $40-100$ AU, corresponds to the location of the Kuiper Belt in our Solar System, and the dust disk was suggested to originate from collisionally disrupted Kuiper Belt-like objects (KBOs) dynamically rejuvenated in the AGB and post-AGB evolutionary stages [15].

SPITZER MIPS 24 μM SURVEY OF HOT WDS

To search for more dust disks similar to that around the WD in the Helix Nebula, we have carried out a *Spitzer* MIPS 24 μm survey of 71 hot ($\sim 100,000$ K) WDs. A compact 24 μm source coincident with the WD is detected in 9 cases; in 7 of these, the star is still surrounded by a PN (Chu et al., 2010, in preparation). We have constructed the SEDs of these WDs using optical and near-IR photometry from the literature. All detections show excess emission at 24 μm. For four of these WDs, we have acquired follow-up *Spitzer*

IRS spectra, and all show dust continuum emission, with some showing additional emission lines. The images and SEDs of three of these targets are shown in Figure 1, and described below.

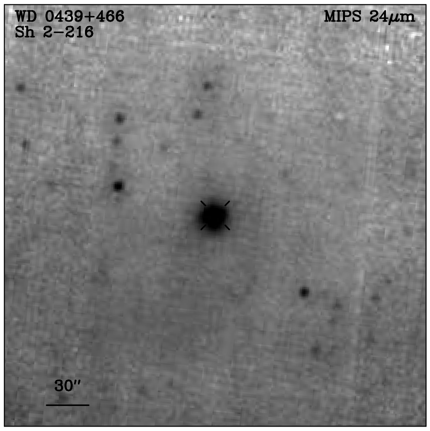
Sh 2-216, at a distance of 219 pc [6], is the closest PN. The SED of its central star follows the blackbody curve from optical to IRAC bands, but shows large excess at 24 μm. The CSPN is not detected at 70 μm; and the SED shows the 3-σ upper limit. The non-detection at 70 μm places constraints on the outer disk radius. The *Spitzer* IRS spectrum is shown in the SED as gray symbols, and the smoothed spectrum is displayed as a thick line. The spectrum is dominated by featureless continuum emission, which starts rising at $\sim$10 μm. Such SED is similar to that of the Helix nebula's CSPN.

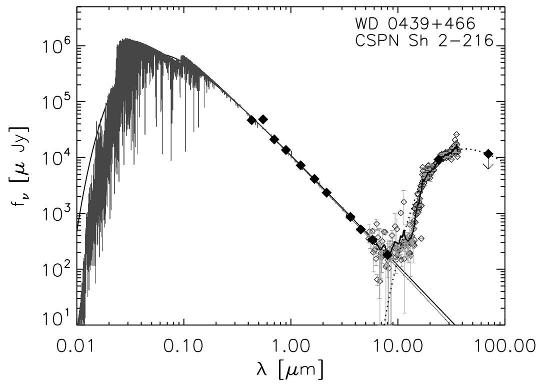
We model the dust emission using an optically thin dust model, assuming that the dust is heated by the central WD. The spectrum does not show mineralogical features; we assume the composition to be astronomical silicates. For the radiation from the WD, we adopt the synthetic spectral model from Rauch et al. [14], the associated WD effective temperature of 95,000 K and log g of 6.9.

Small grains will be blown out of the system due to radiation pressure, and the minimum grain size can be estimated using the ratio of radiation pressure force to gravitational force (β), which depends on WD's luminosity and mass, and the dust grain density. We assume that the grains will be blown out for β of 0.5 [1]. To calculate the luminosity of the WD, we use the distance of 129 pc [6], and integrate the synthetic spectrum normalized to fit the optical and near-IR photometry. We find the WD luminosity of $\sim$40 $L_\odot$. Note that this value is a lower than that derived by Rauch et al. [14], 158.5 $L_\odot$, because of their larger spectroscopic distance, 224 pc. Using the WD luminosity of 40 $L_\odot$, a mass of 0.55 $M_\odot$ [14], and a dust grain density of 2.5 g cm^{-3}, we find the minimum grain size to be $\sim$35 μm. We use a maximum grain size of 1 mm, and assume that larger grains will not contribute significantly to the IR emission. The absorption coefficients are calculated using Mie theory. We also assume a power-law grain size distribution with a power index of -3.5, i.e., $n(a) \propto a^{-3.5}$, typical of collisionally produced dust, and a uniform disk surface density.

The observed fluxes, IRS spectrum, and the 70 μm non-detection can be approximated by emission from a dust disk at radii $\sim$50 to 80 AU, and a mass of $\sim$0.001 $M_\oplus$. Note that the uncertainty in distance affects the calculation of the WD luminosity, which sets the minimum grain size, and subsequently affects the disk's physical parameters. Further exploration of the model's uncertainties is needed.

The *HST* observations of **CSPN K1-22** resolved a red companion 0.35$''$ away from the CSPN [2]. The SED in Figure 2 shows *V* and *I* magnitudes from each star individually [2], the remaining magnitudes are for the two stars combined. The CSPN emission is approximated by a blackbody, and the emission from the companion is a Kurucz model for an M0V star. The two solid curves show contributions from the two components, and the dashed curve shows the sum of these two components. The IR flux densities are all higher than the expected photospheric emission of these two stars. The IRS spectrum shows a continuum component, as well as a strong [OIV] 25.89 μm emission line component, both of which may be contributing to the observed 24 μm excess, but the line emission may also be attributed to incomplete local background subtraction. Due to a poor angular resolution, it is unclear whether the 24 μm source is centered on the CSPN or its red companion, and future high-resolution mid-IR imaging is necessary





to examine the coincidence of the 24μm source and the CSPN.

For purposes of dust disk modeling, we assume that the dust surrounds the CSPN, and the companion is too far and too cool to contribute significantly to the heating of the dust. We approximate the radiation from the CSPN by a blackbody with an effective temperature of 141,000$\pm$31,000 K [13], at a distance of 1.33 kpc [2], normalized to fit the observed optical fluxes. Such approximation yields a luminosity of 325 $L_\odot$, which, together with the mass of 0.59 $M_\odot$ [13], suggests a minimum grain size of $\sim$250 μm. The observed dust continuum can be approximated by a disk extending from the sublimation radius, $\sim$0.62 AU, to $\sim$40 AU, with a dust mass of $\sim$0.002 $M_\oplus$.

Note that the distance to the CSPN is very uncertain, and different authors report values between 1.33 and 3.43 kpc. The large uncertainty in distance introduces a large uncertainty to our dust models, since the distance affects the luminosity calculation, which in turn affects the minimum grain size, and the physical properties of the dust disk.

Another dust disk candidate with SED similar to that of the Helix CSPN is the central star of EGB 1, **WD0103+732**. *HST* images do not show any companion stars [2]. The SED shows optical and near-IR flux densities following the blackbody curve of the hot central WD. 2MASS *H* and *K* data points show upper limits. Follow-up IRAC observations from *Spitzer's* Cycle 5 show that IRAC 3.6, 4.5 and 5.8 fluxes also lie on the blackbody tail, the flux at 8 μm is above the photospheric emission level, and the MIPS 24 μm band flux density is more than three orders of magnitude higher than the expected photospheric emission.

The 24μm image shows that the WD is superposed on diffuse emission, which is dominated by line emission. The background-subtracted spectrum is dominated by dust continuum emission. To model the emission from the WD itself, we use the *UBVRIJHK* photometry from literature and the 2MASS catalog, and the WD parameters from Napiwotzki [12]: distance of 650 pc, effective temperature of 147,000 K, and stellar mass of 0.65 $M_\odot$. Using the blackbody approximation for the WD normalized to fit the optical and near-IR fluxes, we get a luminosity of $\sim$480 $L_\odot$. Therefore, dust grains smaller than $\sim$340 μm will be blown out of the system. Preliminary modeling suggests a dust disk between $\sim$200 and $\sim$360 AU, and a dust mass of $\sim$0.14 $M_\odot$.

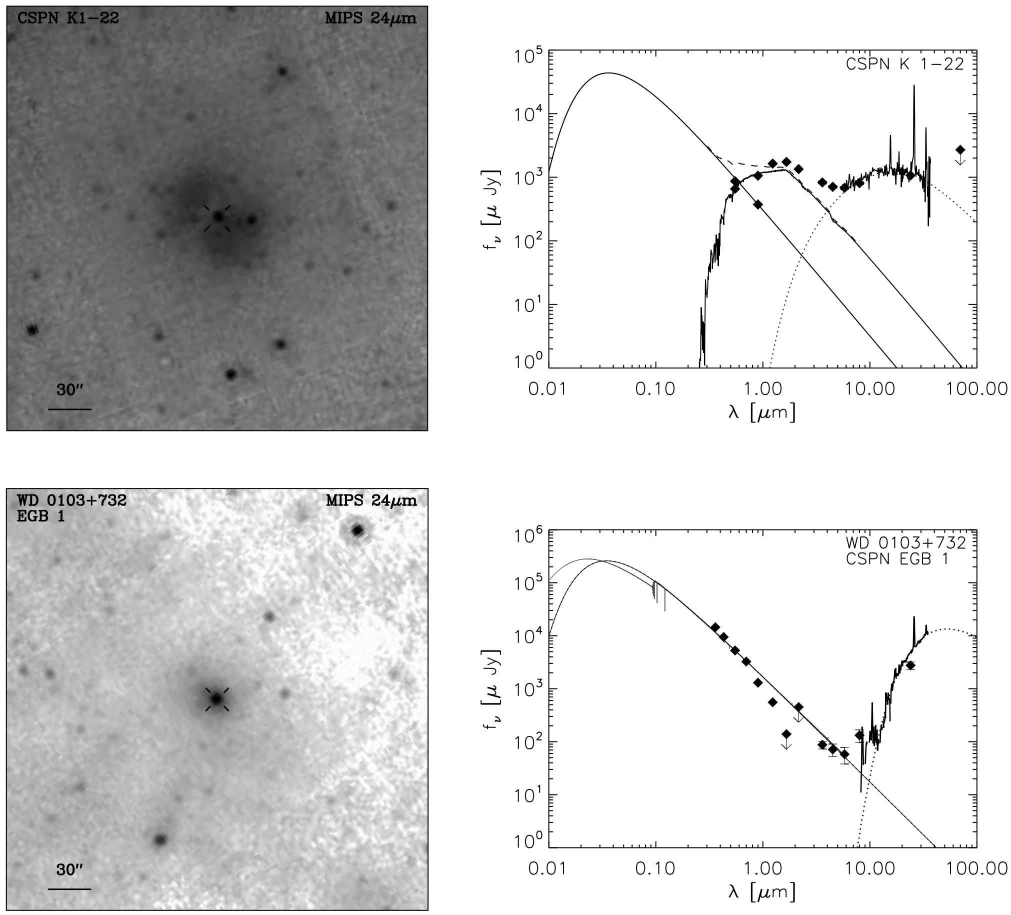


FIGURE 1. SEDs of Sh 2-216, K1-22, and EGB 1 from *Spitzer* 24μm survey. The SEDs are constructed with optical photometry from literature, 2MASS *JHK*, IRAC photometry and *Spitzer* MIPS 24 μm data. The IR spectra from *Spitzer* IRS are shown in solid line for K1-22 and EGB 1. For CSPN Sh2-216, the IRS spectrum is shown in gray symbols, and the smoothed spectrum is shown in solid line. The dotted line represents the dust disk model.

SPITZER ARCHIVAL SURVEY OF CSPNS

Since most cases of hot WDs exhibiting 24 μm excesses are still surrounded by PNe, we have used archival *Spitzer* IRAC (3.6, 4.5, 5.8, and 8.0 μm) and MIPS (24, 70, and 160 μm) observations of PNe to search for CSPNs with IR excesses. We have examined images of 66 resolved PNe, and selected 18 in which the nebular emission was not too confusing or dominant in the central region, and the CSPN was detected in most IRAC bands. For these 18 cases, we have carried out photometric measurements, and constructed the SEDs. Six of these CSPNs show convincing IR excesses.

In the case of NGC 6804 (Figure 2), IR excess is seen starting from *J* band throughout all IRAC channels. The SED does not exclude the possible presence of a cool ($T_{\rm eff} \approx$ 1500 K) companion; however, a companion alone cannot account for all of the observed IR excess, and no companion has been detected around this CSPN [2]. Figure 2 presents a follow-up *Spitzer* MIPS 24μm image, which shows a central source coincident with

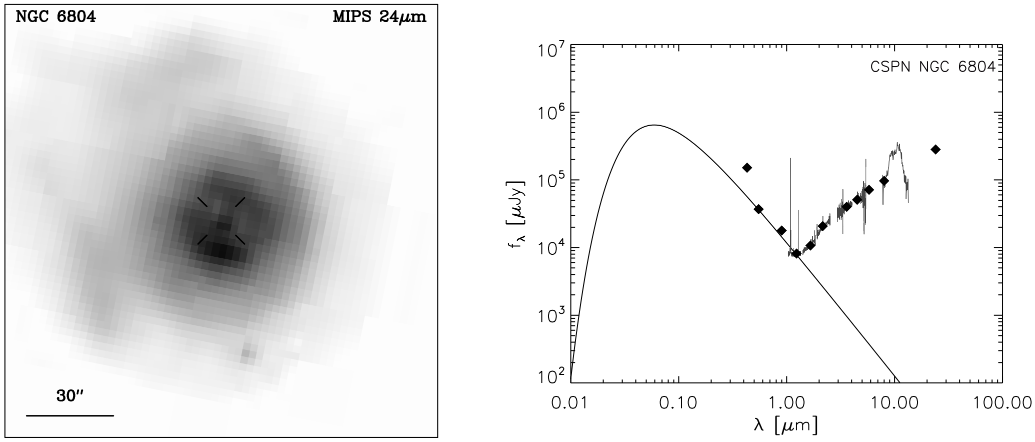


FIGURE 2. *Spitzer* 24 μm image (left) and SED (right) of CSPN NGC 6804. The SED is constructed with optical photometry from literature, 2MASS *JHK*, IRAC photometry and *Spitzer* MIPS 24 μm data. The IR spectra from Gemini's NIRI and Michelle are shown in grey.

the CSPN. The SED displays a follow-up Gemini NIRI 1–5 μm spectrum, which reveals a rising continuum, as well as a compact emission line source. Furthermore, Gemini Michelle 8–15 μm spectrum exhibits a 10 μm silicate emission feature.

POSSIBLE ORIGINS OF IR EXCESSES

The differences between the SEDs of our targets imply different properties of the disks, if not even different origins of excess emission. We need to consider origins other than the collisional disruption of KBOs that can produce the observed IR excesses.

Post-AGB Binary Evolution

It has been suggested from an analysis of broad-band SEDs of 51 post-AGB stars that Keplerian rotating dust disks are common among binary post-AGB stars [5]. van Winckel [16] showed that post-AGB stars displaying SEDs of warm dusty disks are all single-lined spectroscopic binaries and the hot dust persists in the system because it is trapped in a stable circumstellar or circumbinary orbit.

Seven out of 9 hot WDs with 24 μm excesses from our survey and the CSPNs with IRAC and/or MIPS excesses found in the *Spitzer* archive are in PNe and thus represent the youngest WDs that have just evolved past the post-AGB phase. One of them (NGC 2346) has a confirmed binary companion [11] and SED that resembles those of post-AGB binaries; thus, one cannot help asking whether some of these 24 μm and/or IRAC excesses are also related to the IR excesses of binary post-AGB stars reported by de Ruyter et al. [5].

However, it is difficult to identify and confirm the presence of a close companion of a CSPN via direct imaging [2], and irregular spectral variations due to winds hamper

the detection of periodic radial velocity variations [4]. If a dust disk trapped in a stable orbit around a binary system persists throughout the PN phase, its presence can serve as a powerful diagnostic for the binarity of a CSPN. Further observational and theoretical studies are necessary to distinguish between the two origins.

Compact Unresolved Nebulosity

Another possibility is that the observed excess comes from a compact nebulosity with high dust-to-gas ratio, which is seen in the born-again PNe Abell 30 and Abell 78 [3]. This central emission enhancement originates from knots seen in [OIII] λ5007 Å and He II λ4686 Å, but undetected in Hα [9, 7]. Such observed morphological difference implies H depletion in the central region [10], which can occur in born-again PNe [8]. We have carried out KPNO echelle spectroscopy of the hot WDs with 24 μm excesses and CSPNs with IRAC excesses, covering both Hα and [OIII] λ5007 Å lines. In all observed cases, each [OIII] feature has its Hα counterpart. Therefore, born-again scenario cannot explain the observed IR excesses of most of our targets.

SUMMARY

The discovery of a dust disk around the CSPN of the Helix nebula through its 24 μm excess has inspired us to conduct a *Spitzer* 24 μm survey of hot ($T_{\rm eff} \approx 100,000\,$K) WDs. Out of 71 targets observed, 9 show 24 μm excesses, 7 of them in PNe. To find more cases of CSPNs with IR excess, we have searched the *Spitzer* archive, and found 6 targets with convincing IR excesses. While some SEDs are similar to that of the Helix CSPN and show excess emission only in mid-IR, others show excess starting at shorter wavelength. Similarly, while some mid-IR spectra are dominated by dust continuum, others show strong emission lines superposed on dust continuum. The dust around the Helix central star was suggested to be produced by collisions among KBOs [15]. However, other mechanisms that could produce IR excess, such as binary interactions, need to be considered as well. The SEDs and models show a variety of properties. Careful spectral modeling and characterization of the central star are needed to accurately determine the disk properties. Future modeling of the mid-IR SEDs is needed to evaluate the origins of the observed excess emission.

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